# End-To-End Simulations with SIXTE

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https://www.sternwarte.uni-erlangen.de/research/sixte/

# What are End-to-End Simulations?

End-to-end (e2e) simulations: Simulation of the full detection chain for an astronomical instrument, from the astrophysical source through the imaging and detection process to the final data product.

$\Longrightarrow$ Full model of observational setup

E2e simulations have two major "customers":

Scientists:

- Gauge effect of design onto science: Can science goals be reached with the instrument?

  e.g., imaging quality, spectroscopy,...

- What other "observatory" science is possible?
- Plan future observations

Instrumentalists:

- Use science examples to study design: What is impact of design onto science goals?
- Translation of instrument parameters $\Longleftrightarrow$ Science goals
- Estimate instrument performance

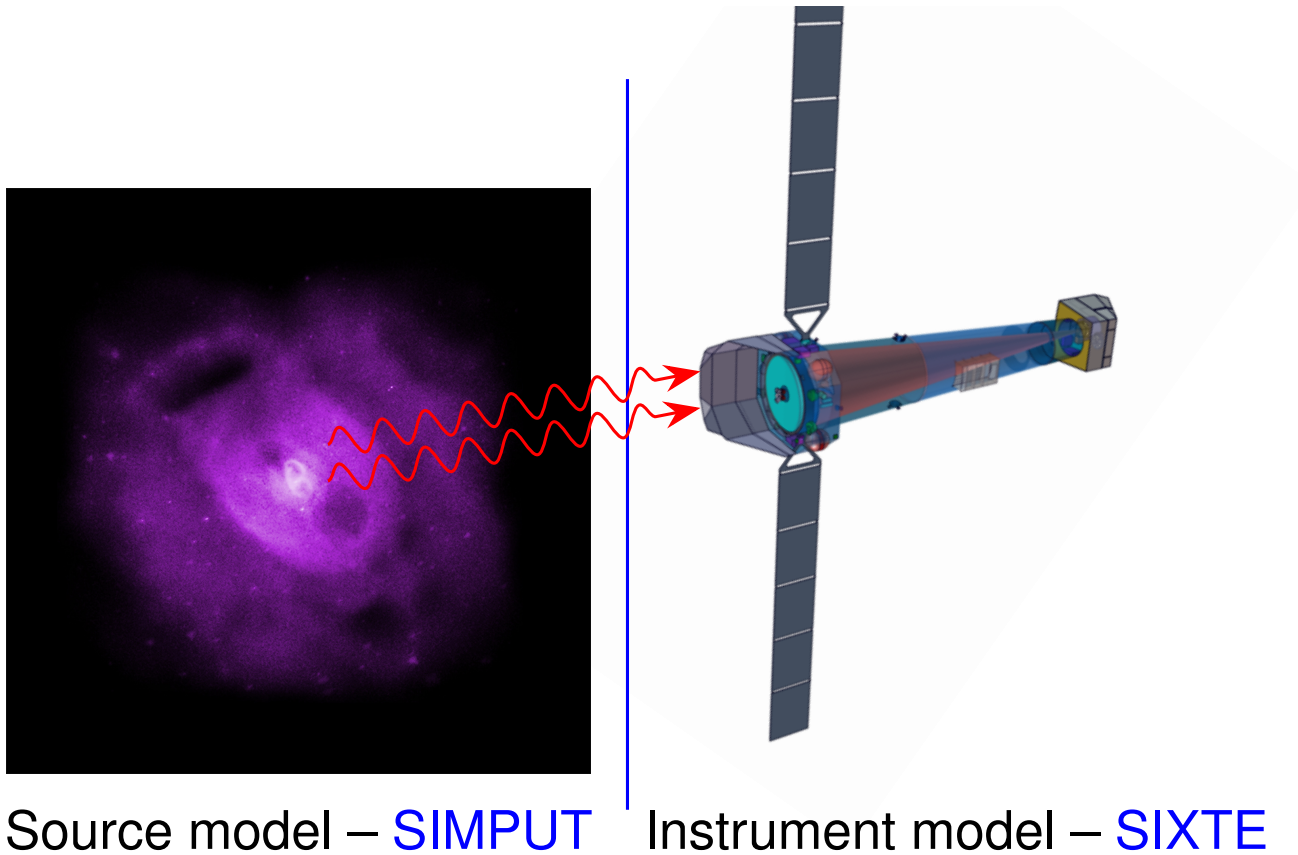  e.g., telemetry constraints, CPU constraints

$\Longrightarrow$ Core component of mission design and implementation!

To be useful, e2e software should always represent best understanding of real instrumental performance.

# What is SIXTE?

# Modeling



Source model – SIXTE     Instrument model – SIXTE

Source model: Define properties of the sources: Positions, Extended source/point source, spectral shape, variability,...

Instrument model: Define properties of the instrument: Imaging parameters, detection process, data processing chain

Output: Data that can be analyzed using standard astronomical analysis software (FTOOLS, XMM-SAS, XSPEC, ISIS,...)

# Source Model: SIMPUT
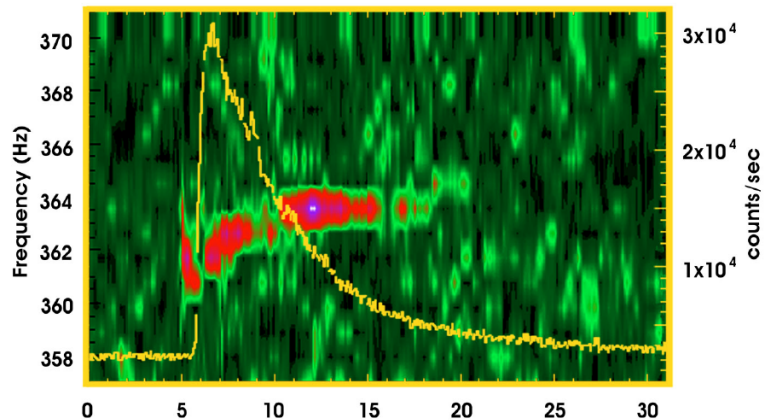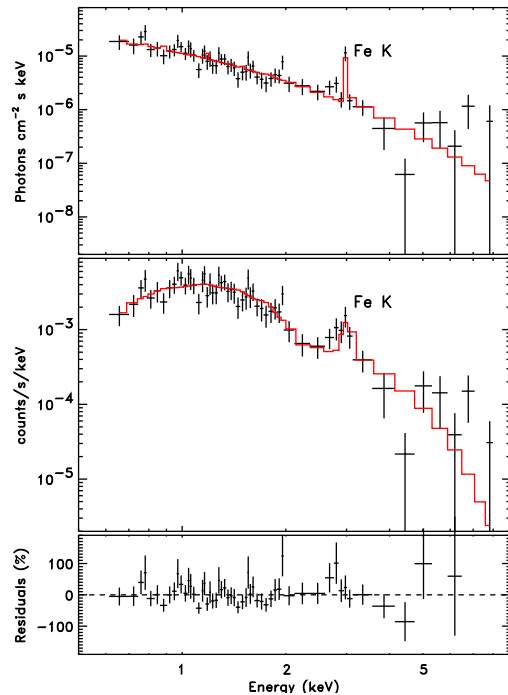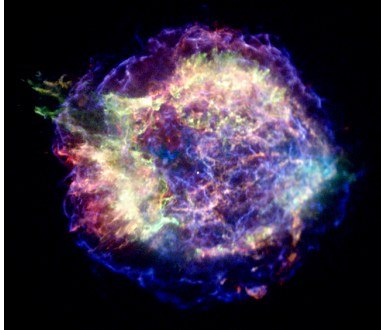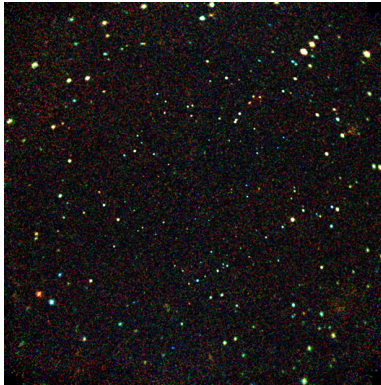


sources are characterized by:

- source properties:
  - spectral shape
  - positions
  - light curves, pulse profiles, power spectra. . .
  - spatial extent
  - photon lists from MHD simulations
  - "data cubes" (e.g., cosmology)
- format allows reuse of common properties of sources

  e.g., reuse AGN spectra for multiple sources, reuse images of extended sources,. . .

- catalogs with arbitrary number of sources

  scales to millions of sources

- compatible w/other simulators

  `simx`, `MARX`

# SIXTE

e2e environment: SIXTE, a generic Monte Carlo simulation framework for X-ray instruments

(Athena, eROSITA, ARCUS, XMM, LOFT, IXO, GRAVITAS,...)

`http://www.sternwarte.uni-erlangen.de/research/sixte`

- modular software → reuse existing algorithms for multiple instruments
- command line driven for longevity

  we will show how to script SIXTE with bash and python
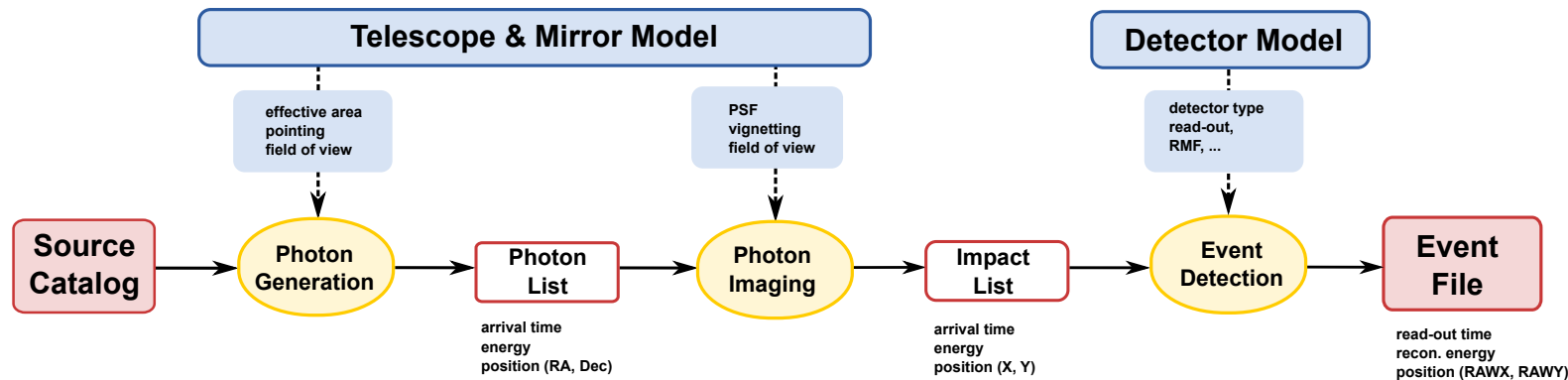


- uses calibration data (response files, PSF, ...) *or* physics-based instrument model
- output: FITS event list (time, energy, pixel)

⟹ *one* simulator for science & technology development

# Instrument model

- **Imaging module**
  - pointing (attitude, e.g., for dithering)
  - ARF
  - vignetting
  - PSF
- **Instrument module**
  - device simulator:
    - **simple/fast simulation:** RMF sampling
    - **advanced simulation:** physics
      (e.g., $T(t)$ for X-IFU, photon effects in Si for WFI)

    flexible focal plane description (XML)
  - other effects considered: pile-up, crosstalk, background, readout
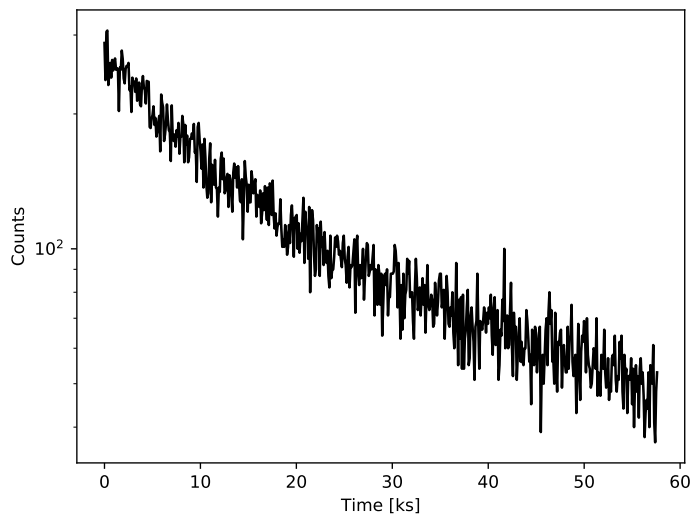- **Output:** FITS event files

large chips (512 × 512)   fast chip (64 × 64)
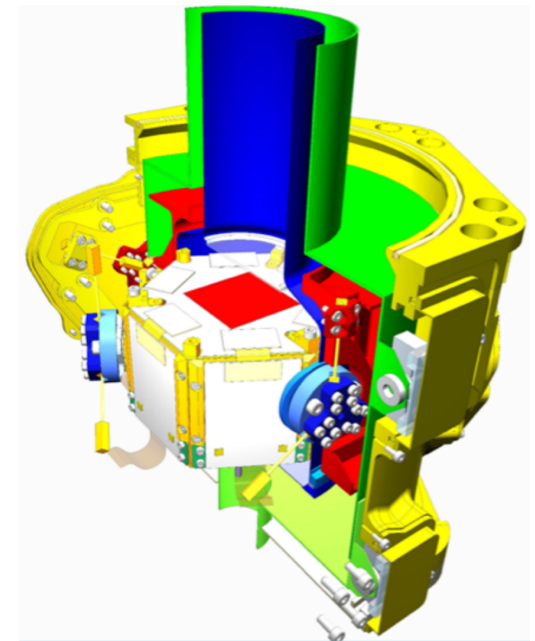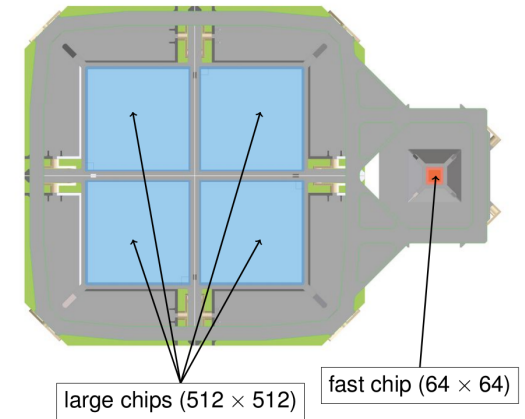
# Example: GRBs and WHIM
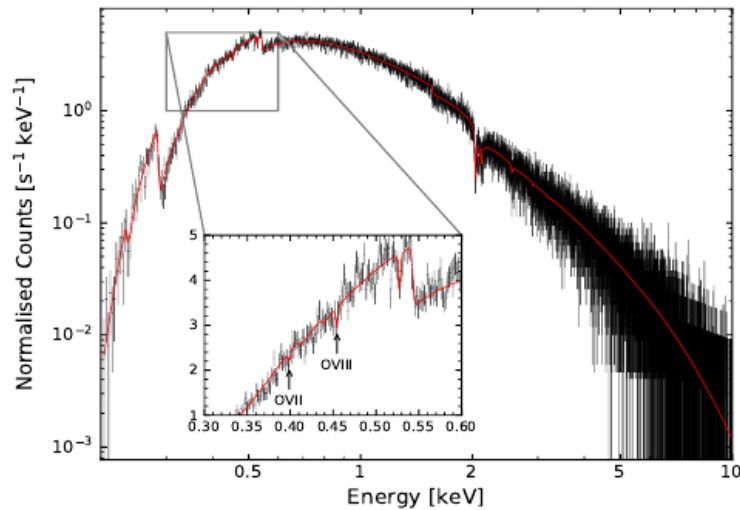
$z_{WHIM} = 0.4388$ Walsh et al. (2020, A&A 642, 24; GRB is at $z = 2$) $z_{WHIM} = 0.0382$
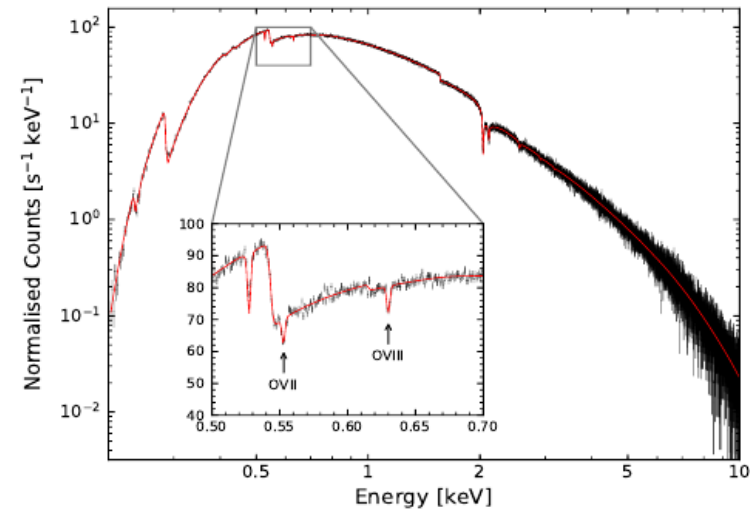
Example: Detection of Oxygen lines from WHIM in GRB spectra

Uses:
- realistic lightcurve
- realistic spectral shape

# Simulation Output



Perseus Cluster at $z$=0.0179

50 kpc

1'
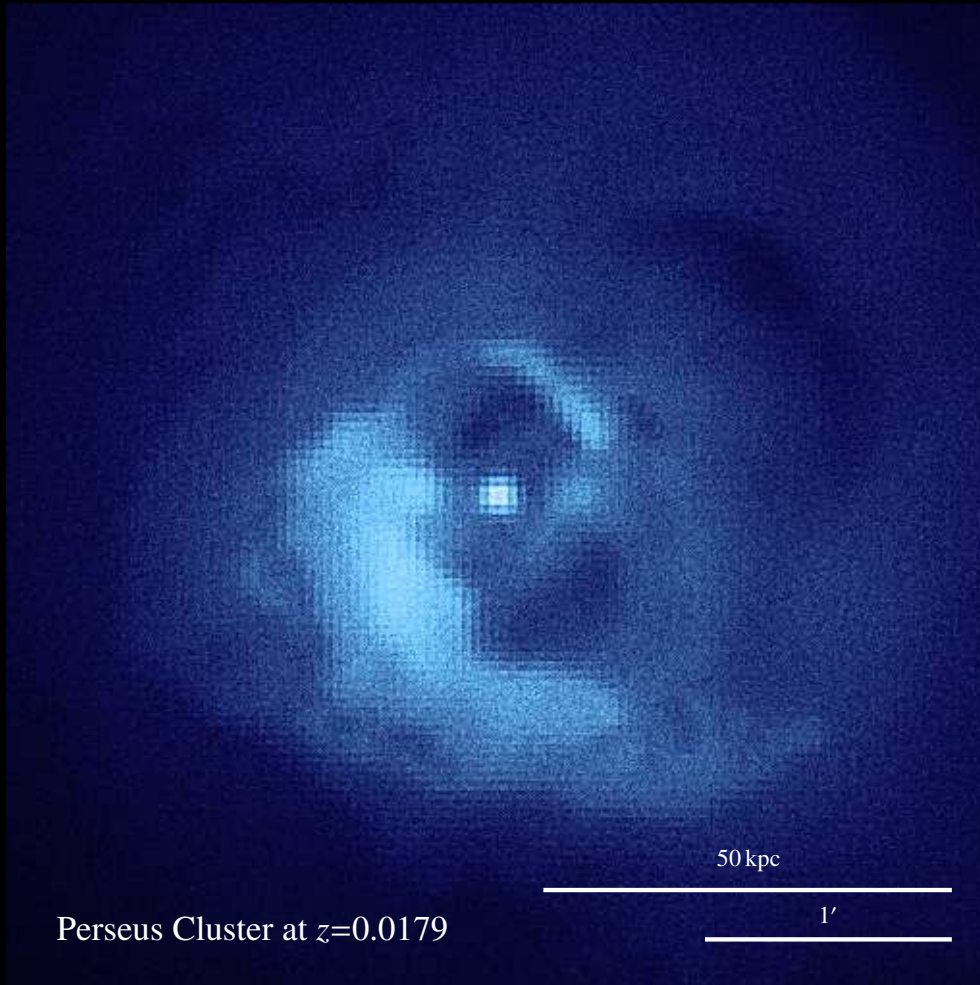
50 ks, one chip

Now shift cluster to higher $z$:

1) Scale cluster size scale via:

$$\phi(z) = \phi_{\mathrm{pers}} \cdot \frac{D_{\mathrm{pers}}/(1+z_{\mathrm{pers}})^2}{D(z)/(1+z)^2}$$

2) Scale flux with luminosity distance:

$$F(z) = F_{\mathrm{pers}} \cdot \left(\frac{D_{\mathrm{pers}}}{D(z)}\right)^2$$

# Simulation Output



z=0.0179

z=0.075

z=0.1

Perseus Cluster at z=0.0179

0.075 z

0.100 z

50 kpc
1'

w/ unsharp masking

z=0.125

z=0.15

z=0.175

0.125 z

0.150 z

0.175 z

50 kpc
1'
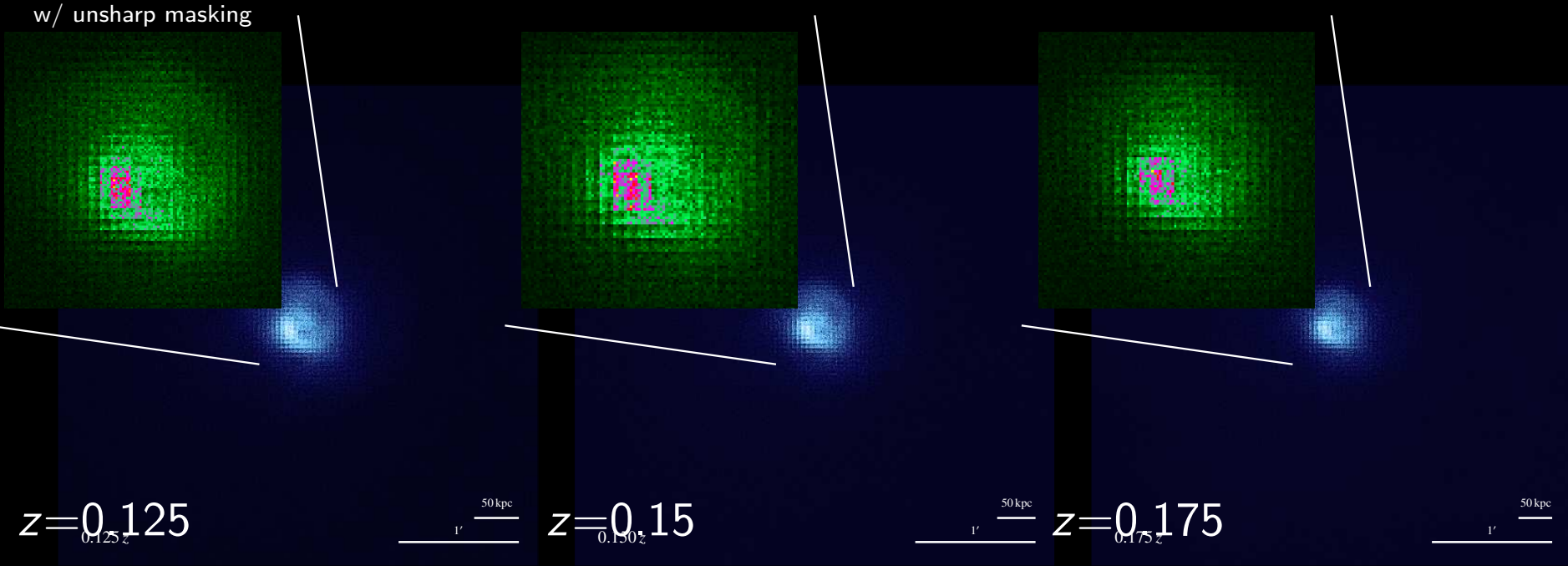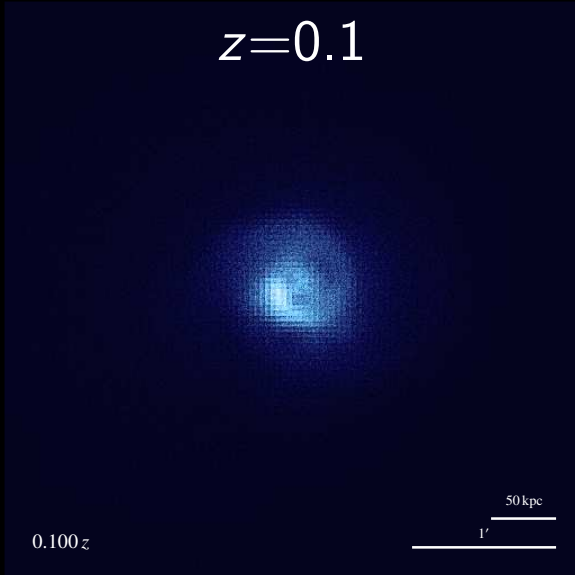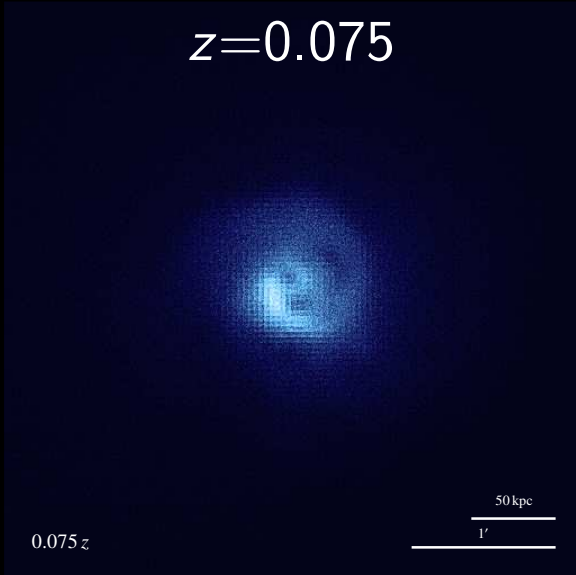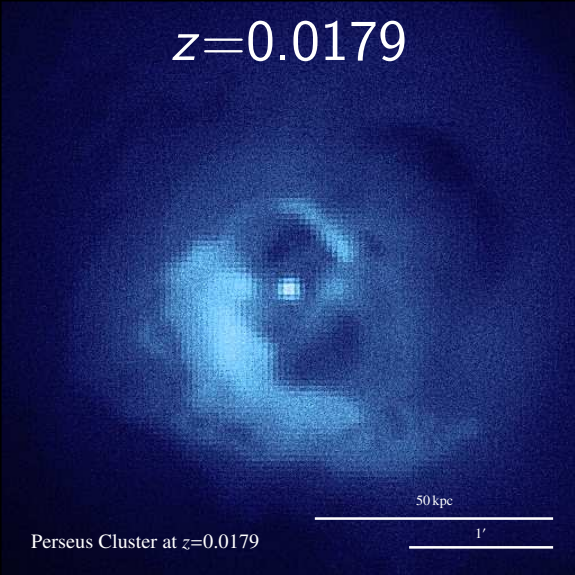
# Example: Galaxy clusters
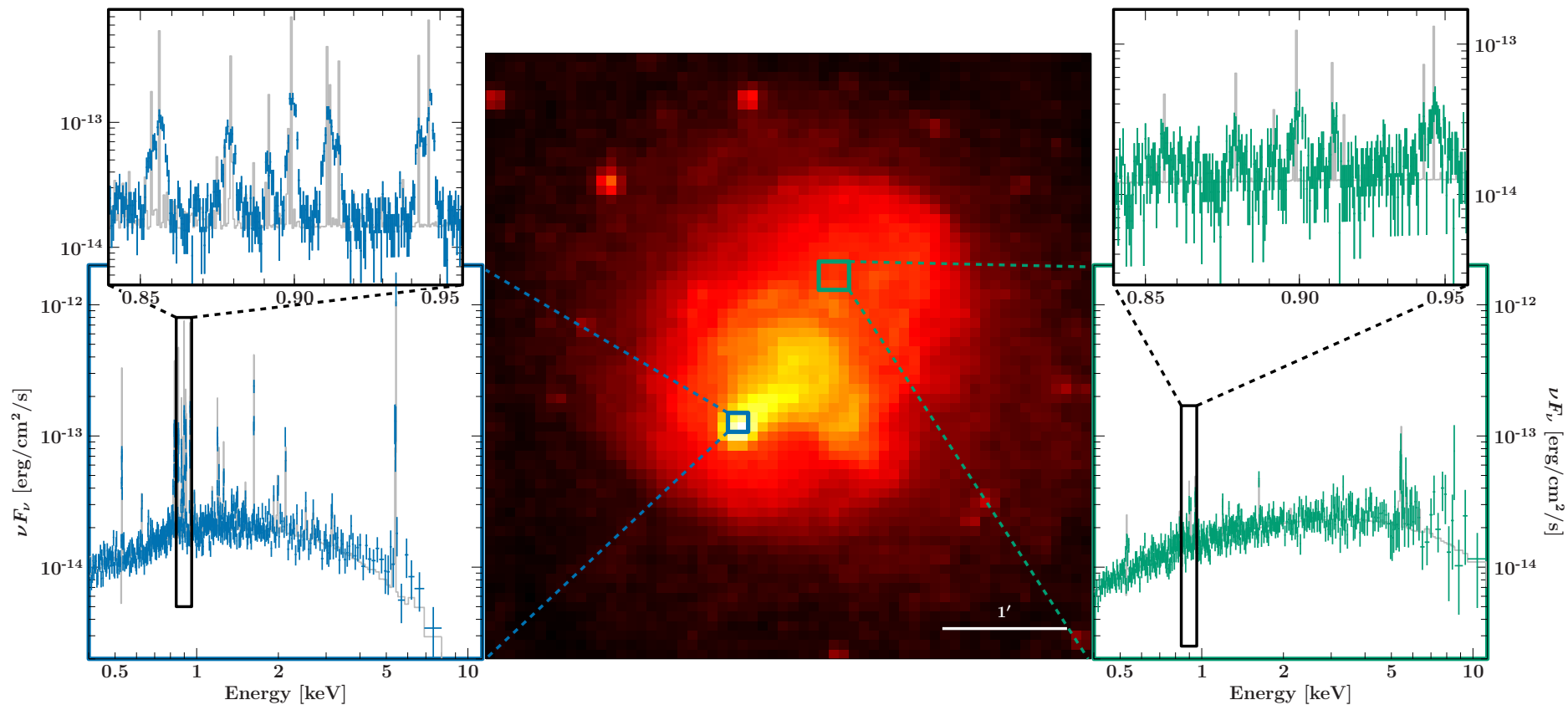


Abell 2146 with X-IFU (T. Dauser/E. Pointecouteau)

# Example: Galaxy clusters
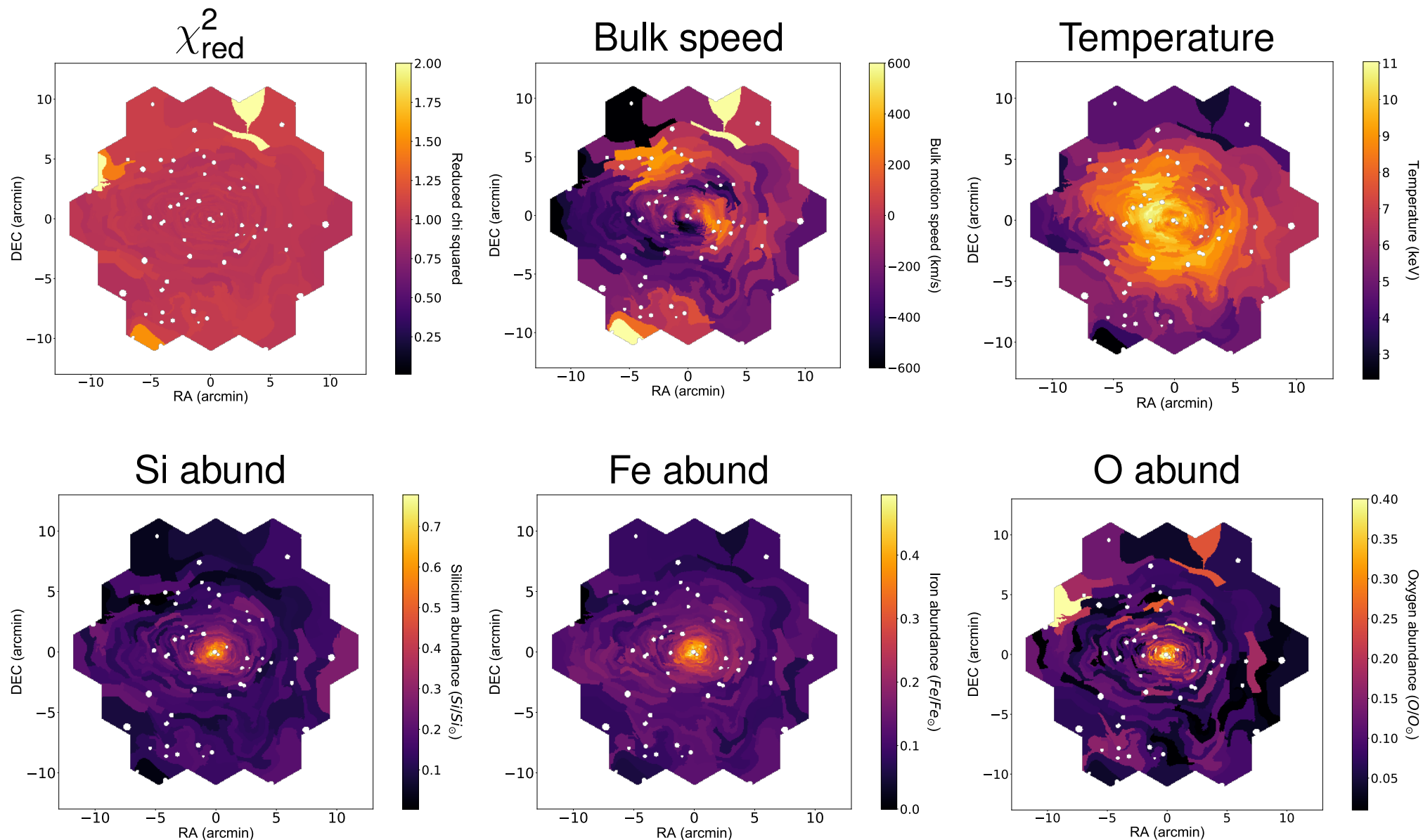


after E. Cucchetti et al. (2018, A&A 620, 173)

# Example: Jupiter
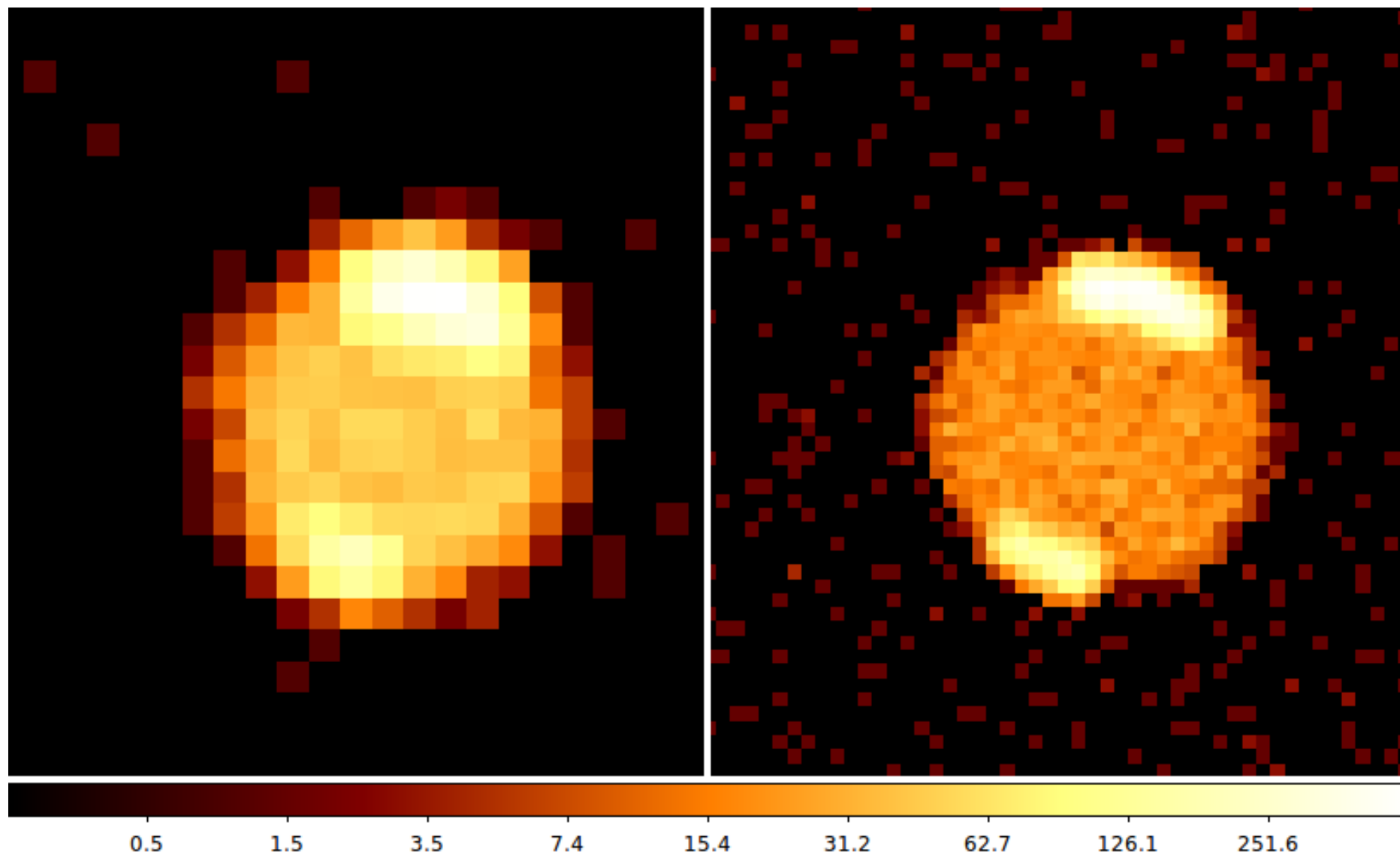


Jupiter in the WFI and the X-IFU (C. Kirsch / G. Branduardi-Raymont)

# Summary



**Access:**

- **documentation**: 96 p. manual and Dauser et al. (2019, A&A 630, 66)
- **help desk**: sixte-support@lists.fau.de
- **Source code**: `http://www.sternwarte.uni-erlangen.de/research/sixte`.
  Works on Linux and Mac, git and release versions; also available on JHU sciserver

# When to SIXTE?

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When not to use SIXTE:

but `fakeit` or similar tools

- fainter point sources ($\lesssim 1\,\text{mCrab}$)

  1 mCrab: $F_{0.5-2\,\text{keV}} = 10^{-11}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$,
  $F_{2-10\,\text{keV}} = 2 \times 10^{-11}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$,

  unless background starts to become important

- quick estimates

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- quick estimates

## When to use SIXTE:

and *not* fakeit

- bright sources ($\gtrsim 10\,\mathrm{mCrab}$)

  i.e., many "famous" AGN

- faint sources if background or exposure map matters

- imaging simulations:

  galaxy clusters, AGN evolution,...

  – point source detection sensitivity
  – point sources in crowded fields
  – extended sources

- variability simulations

  e.g., reverberation mapping, pulsations, QPOs,...

# How to SIXTE?

# This workshop

This workshop:

- Introduction to SIXTE with emphasis on ATHENA

- Software oriented, mixes instrument descriptions with (many) tutorials

- Based on gather town, zoom, SciServer

- Presentations will be recorded

Taught by people with experience in SIXTE:

Thomas Dauser    Christian Kirsch    Ole König    Maite Ceballos

Lea Michalski    Max Lorenz